

PSR J1841–0500: A RADIO PULSAR THAT MOSTLY IS NOT THERE

F. CAMILO¹, S. M. RANSOM², S. CHATTERJEE³, S. JOHNSTON⁴, AND P. DEMOREST²*Accepted for publication, 2011 Nov 24*

ABSTRACT

In a search for radio pulsations from the magnetar 1E 1841–045, we have discovered the unrelated pulsar J1841–0500, with rotation period $P = 0.9$ s and characteristic age 0.4 Myr. One year after discovery with the Parkes telescope at 3 GHz, radio emission ceased from this bright pulsar. After 580 days, emission resumed as before. The \dot{P} during both on states is 250% of the average in the off state. PSR J1841–0500 is a second example of an extremely intermittent pulsar, although with a much longer off period and larger ratio of spin-down rates than PSR B1931+24. The new pulsar is hugely scattered by the ISM, with a fitted timescale referenced to 1 GHz of $\tau_1 = 2$ s. Based on polarimetric observations at 5 GHz with the Green Bank Telescope, the intrinsic pulse profile has not obviously changed between the two on states observed so far, although relatively small variations cannot be excluded. The magnitude of its rotation measure is the largest known, $RM = -3000$ rad m⁻², and with a dispersion measure $DM = 532$ pc cm⁻³ implies a large electron-weighted average magnetic field strength along the line of sight, $7 \mu\text{G}$.

Subject headings: pulsars: individual (PSR B1931+24, PSR J1832+0029, PSR J1841–0500)

1. INTRODUCTION

Rotation-powered pulsars spin down gradually, torqued by their magnetospheric fields and currents. While generally highly predictable, the rotation in some of these neutron stars is occasionally punctuated by “glitches”, sudden period decreases caused by the irregular transfer of angular momentum from the interior to the crust or by crustal rearrangement. Apart from glitches, the observed evolution of rotation is dominated by the predictable effects of electromagnetic torques, but for most pulsars there remains a seemingly random component which makes them somewhat noisy rotators. The ultimate causes of this “timing noise” are not understood.

Recently it has been shown that the timing behavior of several radio pulsars is consistent with oscillation between two discrete values of spin-down rate differing by $\sim 1\%$, which may explain their timing noise to a significant extent (Lyne et al. 2010). In addition, the pulse profiles show changes that are correlated with spin-down rate. This newly identified connection between torque and radiative properties may be related to the long-known but also poorly understood “mode changing” phenomenon, in which some pulsars abruptly change between two discrete average radio profiles (Backer 1970a).

An extreme example of this behavior is apparently provided by PSR B1931+24, with two states lasting for days–weeks in which the spin-down rates differ by $\sim 50\%$ — and in the low state, the pulsar ceases to emit radio pulsations altogether! The discoverers surmise that (extra) magnetospheric currents present in the on state are ultimately responsible for both the radio profile and the extra torque (Kramer et al. 2006). It seems plausible that this could be linked to another long-standing mystery in pulsar phenomenology, “nulling”,

in which the radio emission from some pulsars turns off for several rotations before resuming (Backer 1970b).

Extreme intermittency as displayed by PSR B1931+24 is clearly rare, but its true incidence is not known. This behavior provides a new probe of pulsar magnetospheres, and further examples may lead to a better understanding of some of these phenomena. Here we report the discovery and initial study of PSR J1841–0500, which turned off one year after discovery and resumed pulsations 580 days later.

2. OBSERVATIONS AND RESULTS

2.1. Discovery

Since the first discovery of radio pulsations from a magnetar (Camilo et al. 2006), we had occasionally searched for radio emission from the magnetar 1E 1841–045, located at the center of the supernova remnant (SNR) Kes 73 (G27.4+0.0; Vasisht & Gotthelf 1997). We had done this at the CSIRO Parkes telescope in the 20 cm band (1.4 GHz), but owing to absurdly strong radio frequency interference (RFI) caused by the Thuraya-3 satellite, on Boxing Day 2008 we instead observed in the 10 cm band. We observed the position of the magnetar for 20 minutes at a center frequency of 3078 MHz, using the analog filterbank/PMDAQ system to sample at 1 kHz the total power in each of 288 channels across a bandwidth of 864 MHz before recording to disk. The data were analyzed with standard pulsar search techniques implemented in PRESTO (Ransom 2001), and a strong pulsar with period $P = 0.912$ s and dispersion measure $DM = 530$ pc cm⁻³ was easily identified. This is not the magnetar, which has $P = 11.78$ s.

2.2. Timing, disappearance, and reappearance

We confirmed the pulsar at the NRAO Green Bank Telescope (GBT) on 2008 December 31 with a SPIGOT (Kaplan et al. 2005) observation at 2 GHz and began timing it there on a regular basis. After a couple of weeks we switched to using the GUPPI spectrometer⁵, recording data from a bandwidth of 800 MHz centered on 2 GHz. Each observation

¹ Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA

² National Radio Astronomy Observatory, Charlottesville, VA 22903, USA

³ Department of Astronomy, Cornell University, Ithaca, NY 14853, USA

⁴ Australia Telescope National Facility, CSIRO, Epping, NSW 1710, Australia

⁵ <https://wikio.nrao.edu/bin/view/CICADA/GUPPIUsersGuide/>

typically lasted for 5 minutes and we obtained 39 daily pulse times of arrival between 2009 January 4 and 2010 January 8.

Using TEMPO⁶ we determined a phase-connected timing solution for the pulsar, listed in Table 1 (“Solution 1”). PSR J1841–0500 is located 4′ away from the discovery pointing position, outside the projected extent of the Kes 73 SNR (see Figure 4). The timing solution contains a frequency second derivative (where $\nu = 1/P$), nominally significant at the 6σ level, which whitens the residuals. Inclusion of $\ddot{\nu}$ in the fit changes the values of R.A. and ν by 6σ , decreases the post-fit rms residual from 1.1 ms to 0.9 ms, and presumably reflects timing noise in the pulsar. While the magnitude of $\ddot{\nu}$ suggests a large level of timing noise (see, e.g., Arzoumanian et al. 1994), its impact on rotation is still tiny compared to the effect of $\dot{\nu}$: during 2009, its overall contribution to pulse phase, $\ddot{\nu}t^3/6 = 0.25$, is only 1% of $\dot{\nu}t^2/2$.

We carried on studying the pulsar at the GBT during 2010 and into 2011, but on all 28 observing dates between 2010 January 19 and 2011 July 26 (and on three occasions at Parkes) it was never detected, even after searching the data in period — then, on 2011 August 11, it reappeared at the GBT as bright as ever! It seems that the pulsar turned off for 1.5–1.6 yr. The flux density for each GBT non-detection was $S_2 \lesssim 0.1$ mJy, at least 50 times below the pulsar’s average flux when emitting (Table 1).

We do not of course know that the pulsar was off all the time during those 1.5 yr, only that in every one of 28 attempts, once every 20 days on average, for 5 minutes at a time, we never detected it. Conversely, we detected it on every one of the 43 days that we observed it spanning the previous 1.0 yr. Both of these facts are suggestive of very long continuous either on or off states.

However, one atypical observation serves as a cautionary note: on 2009 December 11 (MJD 55176) the pulsar was detected as usual in a 300 s observation at 17.7^h UT, but in a second observation at 19.9^h it was not detected. After confirming that the equipment was working properly, another 300 s observation was done at 20.0^h and still the pulsar was not detected. Finally, at 20.4^h the pulsar was detected as normal in a 300 s observation. It appears that on this day the pulsar was off for between 10 minutes (700 rotations) and 2.7 hr.

The reality is that during 2009 we observed PSR J1841–0500 for a total of only 4 hr mostly in ≈ 5 minute sessions, or one part in 2000 of the entire year. During a portion of one daily session out of 40, the pulsar turned off, likely for a time amounting to a few percent of the total observing time during the year. Minding the danger of extrapolating from one event, we may suppose that the pulsar actually turned off during 2009 in relatively brief episodes amounting cumulatively to ~ 0.1 –1% of the time. We may also wonder whether during the overwhelmingly off state in 2010 and into 2011 the pulsar occasionally turned on.

We have been timing the pulsar since it reappeared, and have detected it in all nine attempts (once at Parkes). The $\dot{\nu}$ of the new timing solution, measured with 0.5% precision after 66 days, is the same as the one measured in 2009 (“Solution 2” in Table 1). Extraordinarily, the new rotation frequency is well above that expected from the extrapolation of the timing solution in 2009 (see Figure 1 and Table 1): the $\dot{\nu}_{\text{on}}$ measured in 2009 and over the past two months is 2.47 times larger than the average $\dot{\nu}_{\text{off}} \equiv \Delta\nu/\Delta T$ inferred for the off state, computed

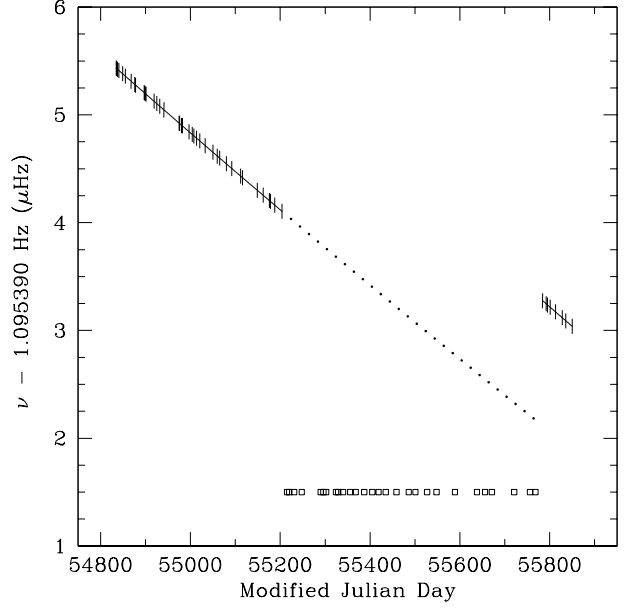


FIG. 1.— Rotation frequency versus date for PSR J1841–0500. The first solid line represents the run of ν from the phase-connected timing solution obtained in 2009. The dotted line is the extrapolation of this trend during the time when the pulsar was not detected. Each small square (placed arbitrarily at a vertical coordinate of 1.5) represents a GBT observing date during this period. The small second solid line, much above the extrapolated trend, is obtained from the timing solution in late 2011, when the pulsar reappeared. Vertical tick marks overlaid on the solid lines represent actual detections.

from the difference in rotation frequencies measured on 2011 August 11 and 2010 January 8 (MJDs 55784 and 55204) from the respective timing solutions, and $\Delta T = 580$ d. Considering the actual observing dates, the off state could have been as many as 27 days shorter than this, which implies a possible $\dot{\nu}$ ratio as large as 2.65. In principle, the frequency offset in Figure 1 could also be interpreted as a glitch with $\Delta\nu/\nu = 10^{-6}$, but it is rare for such large glitches to be observed in pulsars with such relatively small $\dot{\nu}$ (Espinoza et al. 2011), and a glitch has never resulted in the known disappearance of pulses (although in the young and high magnetic field PSR J1119–6127, extra profile components have been detected following a large glitch; Weltevrede et al. 2011). If the mostly on or mostly off states of PSR J1841–0500 are contaminated by their complement, as noted in the previous paragraph, then the true value of the $\dot{\nu}$ ratio would be slightly increased from the nominal value inferred. Also, some of the $\ddot{\nu}$ fitted in 2009 might be due to contamination of mostly $\dot{\nu}_{\text{on}}$ by some $\dot{\nu}_{\text{off}}$. A higher observing cadence could establish the “purity” of the on and off states, and might also help with the interpretation of $\ddot{\nu}$.

2.3. Scattering, pulse profile, and polarimetry

In the discovery observation of PSR J1841–0500, the pulse profile appeared to be scattered by the ISM, despite the high frequency of 3 GHz. This huge level of scattering is confirmed at ≈ 2 GHz (top panel of Figure 2): our fitted scattering functions yield a $1/e$ scattering timescale of $\tau_1 = (2.29 \pm 0.02)$ s, referenced to a frequency of 1 GHz — to our knowledge this is the largest for any known pulsar (with the possible exception of the magnetar 1E1547.0–5408; Camilo et al. 2007), and 100 times larger than predicted by the Cordes & Lazio (2002)

⁶ <http://tempo.sourceforge.net/>

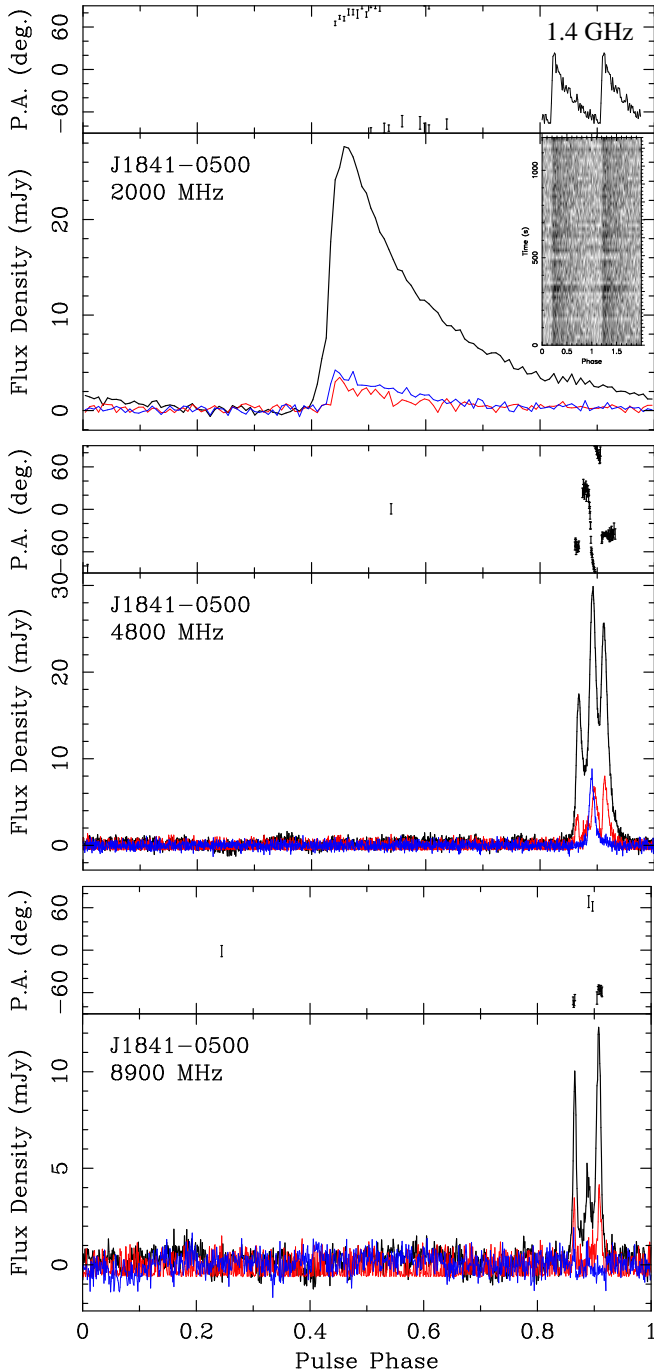


FIG. 2.— Pulse profiles for PSR J1841–0500 at four frequencies. Top: 5 minutes at 2 GHz from 2011 August displayed with 128 bins. The inset shows the only existing 1.4 GHz detection (20 minutes in 2009 October at Parkes), with the pulse profile displayed twice, as a function of time in greyscale and integrated at the top. Middle: 20 minutes at 5 GHz from 2009 September 29 displayed with 2048 bins. Bottom: 23 minutes at 9 GHz from 2009 September 29 displayed with 1024 bins. All polarization data were collected with GUPPI at the GBT. At each frequency the black trace corresponds to total intensity, the red one to linear polarization, and the blue to circular. In all top subpanels we display the position angle of linear polarization, corrected to the pulsar reference frame with $RM = -2993 \text{ rad m}^{-2}$, for bins where the linear signal-to-noise ratio > 3 . The 2 GHz profile is arbitrarily aligned with respect to the two at higher frequencies, and its PA values are essentially meaningless because of scattering. Small wiggles in the off-peak region of the two high-frequency profiles are due to imperfectly removed RFI.

electron density model. In our fits we assumed an intrinsic

pulse profile made up of three gaussians with the central one dominant and its ratio compared to the other two extrapolated from the spectral evolution observed between 5 GHz and 9 GHz (see below and Figure 2). We also assumed that $\tau_f \propto f^{-\gamma}$ with $\gamma = 4$. Fitting for the scattering spectral index results in a somewhat shallower frequency dependence, but the χ^2 of the fit does not improve by much. Nevertheless, it appears that a bit of scattering is still present at 5 GHz (bottom panel of Figure 3), which may support $\gamma < 4$, as has been seen for other pulsars with large DM (Bhat et al. 2004; Löhmer et al. 2001; Löhmer et al. 2004).

We had not detected the pulsar at 1.4 GHz (with 288 MHz of bandwidth) on four previous occasions (in 2006 May and 2007 June and December) and at first assumed that this was due to scattering⁷. In fact the pulsar is detectable at 1.4 GHz when on, as seen in the top panel inset of Figure 2. At this frequency the profile is substantially scattered by more than the rotation period — i.e., some of the flux received at the Earth is not pulsed; however, it is intrinsically bright enough that the remaining pulsed flux is detectable.

Flux-calibrated observations at 2 GHz, 5 GHz, and 9 GHz (shown in Figure 2) yield the period-averaged flux densities listed in Table 1. The uncertainty at 5 GHz is from the difference of two measurements. We have no evidence for significant flux variation due to scintillation, although the 2 GHz observation contains only about 300 pulses (which may not be enough to stabilize the profile), and we assume a 20% uncertainty, as we do at 9 GHz. While the nominal spectrum computed between 5 GHz and 9 GHz is steeper than at lower frequencies, the uncertainties are large enough that we cannot be sure whether this is significant. In any case, $\delta \approx -2$ (where $S_f \propto f^\delta$), and at 1.4 GHz the predicted intrinsic flux density is about 10 mJy.

Although the profile at 2 GHz shows little sign of structure because of the long scattering tail, the 5 GHz and 9 GHz profiles (lower panels of Figure 2) allow us to say a great deal about the classification and geometry of the pulsar. The polarimetric observations were all done with 800 MHz of bandwidth and analyzed with PSRCHIVE (Hotan et al. 2004). The rotation measure was determined to be $RM = -3000 \text{ rad m}^{-2}$, which in absolute value is the largest known for any pulsar. At 5 GHz we also detect numerous single pulses, with peak flux densities up to 200 mJy, and polarization fractions ranging over ~ 0 –100%.

The average pulse profile has three distinct components with the central one most prominent at 5 GHz and significantly less so at 9 GHz. The components at 9 GHz are narrower than at 5 GHz, possibly as a result of residual scattering at 5 GHz. The outer components (separated by $0.042 P$ at both frequencies) do not flank the central component perfectly symmetrically, with the trailing edge closer. The linear polarization is moderate throughout, although characteristically absent on the leading and trailing wings. Circular polarization is seen against the central component but there is no obvious sign reversal. The polarization position angle swing is complex with at least two and possibly three orthogonal mode jumps across the profile (see Figure 3).

The triple structure with a steep spectrum of the central

⁷ We also did not detect the pulsar in a subsequent reanalysis of the closest pointing of the Parkes multibeam survey (Manchester et al. 2001) to the pulsar position, 4.5° away, from 1998 August. In addition, the pulsar was not detected by Lazarus et al. (2011) in a 2006 November GBT search of the nearby magnetar.

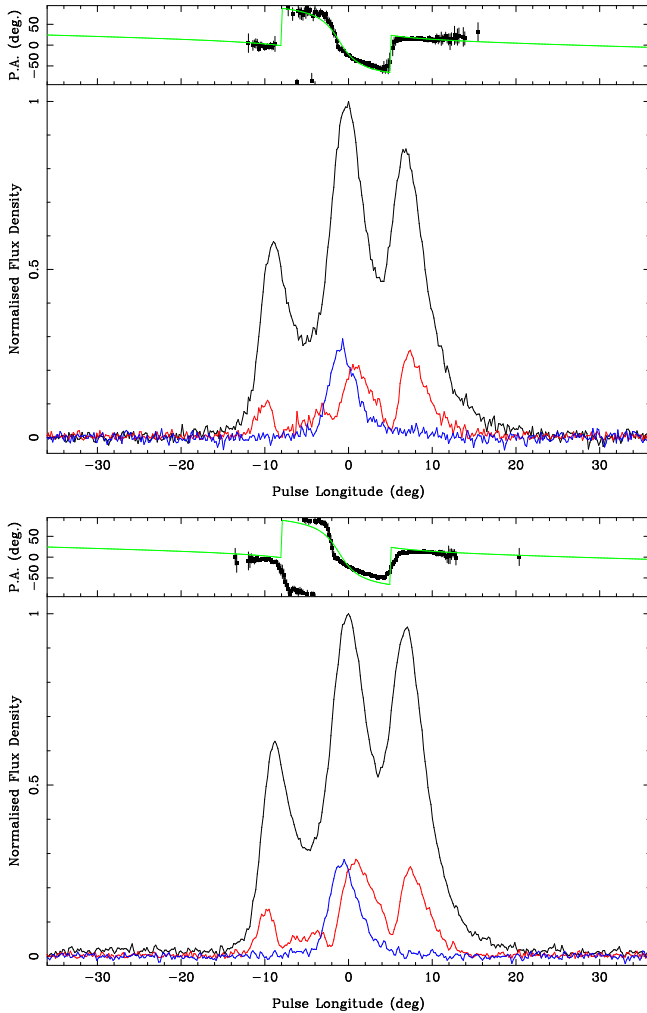


FIG. 3.— Rotating vector model fit to 5 GHz data of PSR J1841–0500. Top: 2009 profile, shown in the middle panel of Figure 2, zoomed in on the emission region, along with RVM curve (green) fitted to position angles where linear polarization signal-to-noise ratio > 2 (black). Bottom: 2011 profile, based on 50 minutes of data. For comparison, we plot in green the RVM model obtained for the 2009 data. In neither case have the PAs been rotated to the reference frame of the pulsar.

component is characteristic of many pulsar profiles (Rankin 1993). The central component likely originates near the magnetic pole with the outer components forming a cone of emission at some reasonable fraction of the distance to the edge of the polar cap. The measured full width is some 25° . This is much larger than the $\sim 14^\circ$ derived under the assumption that the emission height is ~ 300 km, typical of older pulsars (Mitra & Rankin 2002). This then implies that either the emission height is much larger (greater than 1000 km) or that the value of α (angle between the magnetic and spin axes) is less than 45° .

In the middle panel of Figure 2, the steep position angle of linear polarization under the main peak hints at a small impact parameter β (closest approach between the observer line of sight and the magnetic axis). However, when we look at the profiles and PAs in more detail (Figure 3), reality appears much more complicated. We show in the top panel of Figure 3 a rotating vector model fit (Radhakrishnan & Cooke 1969) to 5 GHz data from 2009. The PAs in the outer pulse components are apparently offset by 90° with respect to the

adjoining PAs in the middle component; the fit in the middle component seems to capture the major trend of PA (and taken at face value implies $\beta \lesssim 3^\circ$) but clearly there are unmodeled details.

The inadequacies of the RVM fit and complicated PA structure of the profile are seen more clearly in the bottom panel of Figure 3, where we show 5 GHz data from 2011, with higher signal-to-noise ratio. The RVM model shown here is the one obtained from the fit to 2009 data, and clearly does not fit well the complex progression of PA across the profile. Karastergiou (2009) has shown that orthogonal jumps in PA together with even modest levels of scattering can distort observed PA swings, and this may be occurring for PSR J1841–0500 at 5 GHz. In that case, even our supposition that β may be small is not necessarily correct.

The two 5 GHz profiles differ slightly (e.g., the total intensity third component is relatively stronger in 2011; there are also slight differences in polarized flux). In order to investigate whether these differences are meaningful, we split the 2011 observation into two equal halves. The profiles differ from each other by more than the noise level, although by a little less than the 2009–2011 difference. It is conceivable that 1500 rotations are not enough to generate a stable average pulse profile. It is also possible that RFI contamination is responsible for some of these differences (see off-pulse RFI in the middle panel of Figure 2). Further observations are required in order to reach credible conclusions concerning the stability of the PSR J1841–0500 profile (the two 5 GHz and one 9 GHz observations presented here are the only ones that exist at frequencies greater than 3 GHz).

2.4. The radio and X-ray neighborhood of PSR J1841–0500

PSR J1841–0500 is located right on the Galactic plane, at $b = -0.03^\circ$, and this location has been imaged multiple times at radio wavelengths. In the left panel of Figure 4 we show the most beautiful existing image of its surroundings. This is extracted from the MAGPIS survey (Helfand et al. 2006) at a wavelength of 20 cm, and the image has an approximate angular resolution of $6''$ and rms sensitivity of 0.3 mJy. PSR J1841–0500 (with position indicated by a circle) is not detected, with a 3σ upper limit of 1 mJy (the point sources to the west and northwest of the pulsar have flux densities of 6 mJy and 5 mJy, respectively). At 2 GHz the pulsar flux density is $S_2 = 5$ mJy, and we estimate (Section 2.3) that $S_{1.4} \approx 10$ mJy — when the pulsar is turned on! Evidently, when the multi-epoch VLA and Effelsberg observations for this image were done, the pulsar was not on.

The SNR Kes 73 and its magnetar have been observed with the *Chandra* X-ray Observatory, and the new pulsar falls within the field of view. We have reprocessed two observations using the latest CIAO pipeline⁸, from which we determine an upper limit for X-ray emission from PSR J1841–0500.

In a 29 ks ACIS-I observation (ObsID 729, done in 2000 July), only one photon is detected in the 0.5–7 keV range within a circle of radius $2''$ centered on the pulsar. The background level is high due to the nearby SNR, and the source falls near a chip boundary. The exposure-corrected upper limit on the 0.5–7 keV count rate is $1.2 \times 10^{-4} \text{ s}^{-1}$ at the 90% confidence level. A slightly better exposure-corrected 90% upper limit of $9.4 \times 10^{-5} \text{ s}^{-1}$ is derived from a 25 ks ACIS-S

⁸ <http://cxc.harvard.edu/ciao/>

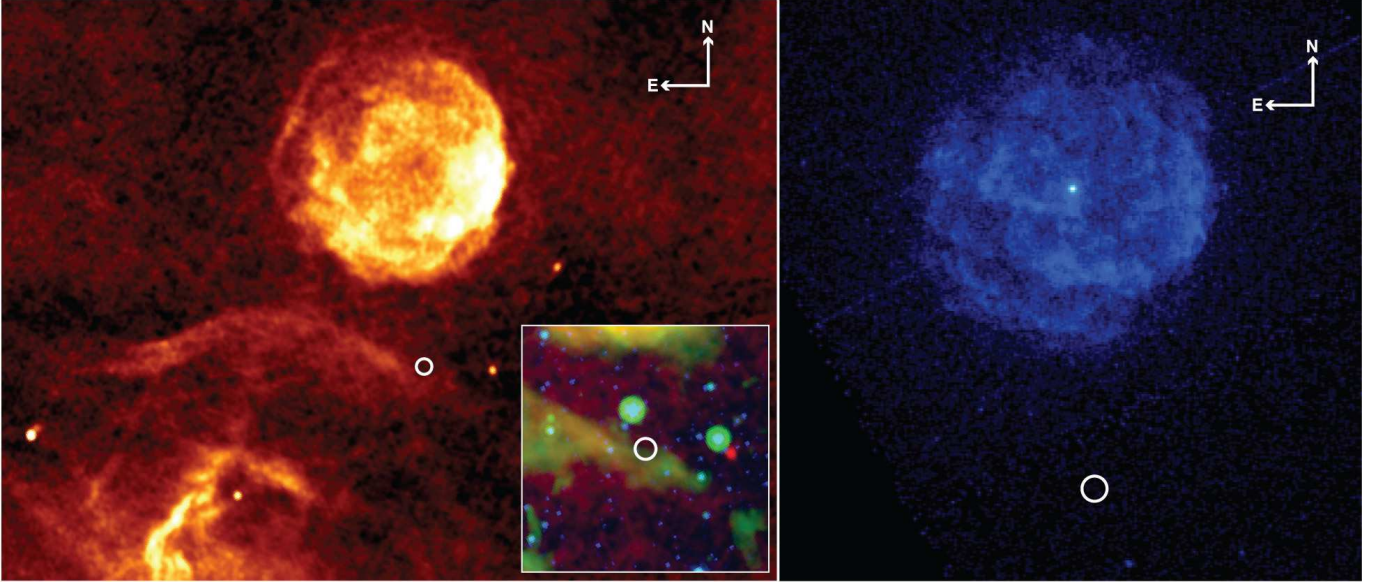


FIG. 4.— The neighborhood of PSR J1841–0500. In all panels, the pulsar position (known with $\approx 1''$ accuracy) is indicated by a circle $10''$ in radius. Left: MAGPIS radio (1.4 GHz) image (Helfand et al. 2006), $16' \times 12'$, showing the circular SNR Kes 73 and the location of PSR J1841–0500 to its south. Inset: $4' \times 4'$ multi-wavelength view centered on the pulsar location, showing MAGPIS 1.4 GHz in red, MIPS GAL $24\mu\text{m}$ in green, and GLIMPSE $3.6\mu\text{m}$ in blue. Right: *Chandra* ACIS-S X-ray (0.5–7 keV) exposure-corrected image, $8' \times 8'$ with $2''$ resolution, showing SNR Kes 73 with its central magnetar 1E 1841–045 and the position of PSR J1841–0500. All datasets except for $3.6\mu\text{m}$ have huge dynamic range and are presented with logarithmic scaling.

observation (ObsID 6732, done in 2006 July), in which no counts are detected within the same aperture.

Assuming a putative power-law spectrum with photon index $\Gamma = 1.5$ absorbed by a column with $N_H = 1.6 \times 10^{22} \text{ cm}^{-2}$ (corresponding to one free electron for every 10 neutral hydrogen atoms along the line of sight), this implies an unabsorbed flux of $f_X < 2 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$, or luminosity $L_X < 10^{30} (d/7 \text{ kpc})^2 \text{ erg s}^{-1}$. For a distance of 7 kpc, as inferred from the DM and the Cordes & Lazio (2002) model, $L_X/\dot{E} < 6 \times 10^{-4}$. For SNR Kes 73, at $7.5 \text{ kpc} < d < 9.4 \text{ kpc}$ (Tian & Leahy 2008), $N_H = (2-3) \times 10^{22} \text{ cm}^{-2}$ (Vasisht & Gotthelf 1997); the huge amount of scattering for PSR J1841–0500 (Section 2.3) also suggests that there might be more X-ray absorption or scattering than assumed, so that a more realistic limit might be $L_X/\dot{E} < 10^{-3}$ or even higher. At such levels, the non-detection of PSR J1841–0500 in X-rays is not surprising (see, e.g., Possenti et al. 2002).

3. DISCUSSION

PSR J1841–0500 is an extremely intermittent pulsar, the only one besides PSR B1931+24 to have been reported on in detail. Some differences are that the off state of PSR J1841–0500 is $\sim 20\times$ longer than for PSR B1931+24, the ratio of on-to-off $\dot{\nu}$ is 2.5 rather than 1.5, and at this point we still do not know whether the on-off cycles in PSR J1841–0500 occur quasi-periodically, since we have only observed one off interval surrounded by two on phases, the first of which lasted for at least 1 yr. (The five non-detections in 2006–2007 are consistent with another off period lasting also for ~ 600 days; see Section 2.3.) Although published details are limited, a third such pulsar is known: PSR J1832+0029 (Lorimer et al. 2006) was observed to turn off for about 2 yr between two 1 yr on phases, with a ratio of on-to-off $\dot{\nu}$ of 1.7 (Kramer 2008; Lyne 2009).

We do not know what causes these (or any) pulsars to turn off, or back on. But any plausible magnetospheric model should attempt to account for the observed on-to-off ratios

of $\dot{\nu}$, which now span 1.5–2.5 for three pulsars. Models of pulsar magnetospheres range between those that contain no plasma, where $\dot{\nu} \propto 2 \sin^2 \alpha / 3$ (e.g., Manchester & Taylor 1977), and ideal MHD plasma-filled descriptions where $\dot{\nu} \propto 1 + \sin^2 \alpha$ (Spitkovsky 2006; Kalapotharakos & Contopoulos 2009). None of these can explain actual pulsar emission: the vacuum models have no charged particles that can be accelerated and radiate, while the “force-free” models have $\vec{E} \cdot \vec{B} = 0$ and cannot accelerate the charged particles to radiate. On the plus side, quantitative solutions exist for these limiting cases for arbitrary inclinations α (see, e.g., Spitkovsky 2006). In the context of these models it may be tempting to associate the pulsar on states with a force-free magnetosphere and the pulsar off states with a vacuum magnetosphere, but the $\dot{\nu}$ ratios for those models are always > 3 , not matched by the observations. Recently, Li et al. (2011) and Kalapotharakos et al. (2011) have computed resistive solutions for pulsar magnetospheres that in significant respects lie between these extrema. Associating the on state with the force-free magnetosphere and the off state with a resistive configuration (i.e., with a suppression of the conduction current, for unknown reasons), these finite conductivity models can produce the observed $\dot{\nu}$ ratios for any value of α , including intermediate ones (which we expect a priori, given that only three of these intermittent pulsars are known; for smaller α , the $\dot{\nu}$ ratios should be larger, all else being equal). It seems encouraging that these advances in the treatment of pulsar magnetospheres provide a framework that may help to explain the unexpected observations of two-state $\dot{\nu}$ in PSRs B1931+24, J1832+0029, and J1841–0500.

Pulsar intermittency is observed with a huge variety of on and off timescales. Rotating radio transients (RRATs) are sporadic emitters of isolated radio pulses (McLaughlin et al. 2006), and while much remains unclear about RRATs, some of them may represent simply a more extreme form of the classical nulling phenomenon (see Burke-Spolaor & Bailes

2010), with nulling fractions of up to $> 99\%$. Where do PSR J1841–0500 and its two identified cousins fit in this scheme? Their overall nulling fractions (about 20–40%) are not particularly large, but the average time off between on states is exceptional: for nulling pulsars and RRATs, this ranges smoothly between seconds and ≈ 1 hr, but it is ≈ 1 month for PSR B1931+24, and ≈ 1 yr for PSR J1841–0500. Based in part on these observations, Burke-Spolaor et al. (2011) argue that the intermittency of PSR B1931+24 represents a distinct phenomenon to nulling/RRATing, and this conclusion applies even more so to PSR J1841–0500. What type of pulsar can display extreme intermittency like PSRs B1931+24, J1832+0029, and J1841–0500? RRATs, on average, may occupy a special location in the pulsar P – \dot{P} diagram, with longer periods and larger inferred surface magnetic field strengths than the bulk of the population (McLaughlin et al. 2009). Magnetars can be transient radio emitters (e.g., Camilo et al. 2006), but they certainly occupy a distinct quadrant of the P – \dot{P} diagram. But PSRs B1931+24, J1832+0029, and J1841–0500 as a group occupy an unremarkable location in P – \dot{P} , and apart from their intermittency and associated torque changes there does not appear to be anything exceptional about them. Can other apparently ordinary pulsars display this behavior at some point during their $\sim 10^7$ yr radio lifetimes, perhaps with even longer off (and on) timescales? Maybe some pulsar that has been observed steadily for decades will one of these years disappear, not to return in our lifetimes, but returning eventually after centuries dormant.

Quite apart from its unusual radiative and rotational properties, PSR J1841–0500 is somewhat unusual in being located only $4'$ from another (very young) neutron star, the magnetar 1E 1841–045 within the SNR Kes 73. In the ATNF pulsar catalog (Manchester et al. 2005)⁹, there are 11 neutron star pairs listed with separations $< 4'$, among 1794 pulsars in the Galactic disk. The probability of finding such a pair by chance is therefore of order 1%. The distance estimates that we have for both of these objects are compatible, at approximately 8.5 kpc. The question therefore arises of whether this is merely a coincidence. At that distance, the angular separation corresponds to 10 pc. If both progenitor stars had been in a binary system that disrupted upon the second supernova explosion (SNe), then for an assumed magnetar/SNR age of 10 kyr, the implied transverse velocity is nearly 1000 km s^{-1} , which is large but not impossibly so. However, one might then have expected evidence for the passage of a high-velocity neutron star through the SNR shell (see, e.g., Camilo et al. 2009). In addition, the SNR is probably much younger (≈ 1000 yr according to Tian & Leahy 2008). If on the other hand the putative binary had disrupted upon the first SNe, the implied transverse velocity is much smaller, $\sim 10 \text{ km s}^{-1}$. Even if PSR J1841–0500 and 1E 1841–045 are not directly associated, it is plausible that they might both have been born in the same young stellar cluster.

The remaining puzzle concerning PSR J1841–0500 is its huge RM and amount of scattering. At a distance of 7 kpc, the pulsar is located on the inside edge of the Scutum spiral arm, where RMs are predominantly positive with $|\text{RM}| < 500 \text{ rad m}^{-2}$, reflecting the counterclockwise large-scale magnetic field of the Crux-Scutum arm (Han et al. 2006). For PSR J1841–0500, the $\text{RM} = -3000 \text{ rad m}^{-2}$ must be largely

due to one or more discrete intervening sources along the line of sight, for instance an SNR. The anomalously large level of scattering is presumably also caused by discrete sources, for instance an HII region or SNR. In the left panel of Figure 4 we see that the pulsar is located in projection extremely close to the boundary of an arc that may surround a larger structure to the south. It is not clear whether this “wisp” is thermal or non-thermal in nature. The radio filament at 20 cm exactly overlaps a $24 \mu\text{m}$ filament detected in the MIPS GAL *Spitzer* infrared survey¹⁰ (see the inset in Figure 4). However, there is no corresponding emission detected in the GLIMPSE survey at $3\text{--}8 \mu\text{m}$ ¹¹, suggesting that the dust in this region is fairly cold and likely not part of an HII region (in contrast, the bright filament to the southeast of the pulsar, aligned along a southeast–northwest direction, is clearly thermal). Perhaps this is an old SNR shell filament that could account for the scattering and the high line-of-sight magnetic field for PSR J1841–0500, if the pulsar lies behind it.

Much of the Galactic plane has been surveyed for pulsars with good sensitivity, but for the most part it has not been searched *repeatedly*. The detection of intermittent pulsars would benefit from long-term wide-field imaging surveys for slow radio transients. For pulsars that are as, or more, scattered than PSR J1841–0500, traditional surveys require a high frequency, with the drawbacks of small telescope beam size and small pulsar flux (see Bates et al. 2011). Imaging surveys might prove to be a more efficient method to discover such pulsars.

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Facilities: Parkes (PMDAQ), GBT (GUPPI)

¹⁰ See <http://mipsgal.ipac.caltech.edu>. Multi-wavelength views of this busy region of the Galactic plane can be obtained at <http://third.ucllnl.org/cgi-bin/colorcutout>.

¹¹ <http://www.astro.wisc.edu/sirtf/>

⁹ <http://www.atnf.csiro.au/research/pulsar/psrcat/>

TABLE 1
MEASURED AND DERIVED PARAMETERS FOR PSR J1841–0500

Parameter	Value
Data span (MJD)	54835–55204 (Solution 1)
Right ascension, R.A. (J2000.0)	18 ^h 41 ^m 18 ^s .14(5)
Declination, decl. (J2000.0)	−05°00′19″.5(8)
Rotation frequency, ν (s^{-1})	1.0953947642(3)
Frequency derivative, $\dot{\nu}$ (s^{-2})	$-4.165(1) \times 10^{-14}$
Frequency second derivative, $\ddot{\nu}$ (s^{-3})	$4.8(8) \times 10^{-23}$
Epoch of frequency (MJD)	55018.0
Data span (MJD)	55784–55850 (Solution 2) ^a
Rotation frequency, ν (s^{-1})	1.0953931969(2)
Frequency derivative, $\dot{\nu}$ (s^{-2})	$-4.17(2) \times 10^{-14}$
Epoch of frequency (MJD)	55800.0
Dispersion measure, DM (pc cm ^{−3})	532 ± 1 ^b
Rotation measure, RM (rad m ^{−2})	−2993 ± 50
Flux density at 2 GHz, S_2 (mJy)	5.4 ± 1.1
Flux density at 5 GHz, S_5 (mJy)	1.1 ± 0.1
Flux density at 9 GHz, S_9 (mJy)	0.23 ± 0.05
Galactic longitude, l (deg)	27.32
Galactic latitude, b (deg)	−0.03
DM-derived distance, d (kpc)	7
Characteristic age, τ_c (yr) ^c	$\{0.4, 1.0\} \times 10^6$
Spin-down luminosity, \dot{E} (erg s ^{−1}) ^c	$\{1.8, 0.7\} \times 10^{33}$
Surface dipole magnetic field strength (Gauss) ^c	$\{5.7, 3.6\} \times 10^{12}$

NOTE. — Numbers in parentheses represent the nominal 1 σ TEMPO timing uncertainties on the last digits quoted.

^a For this solution, the celestial coordinates were held fixed at the value obtained in Solution 1.

^b This is a scattering-corrected DM.

^c These derived quantities are computed using the value of $\dot{\nu}$ in the on and off state, respectively.

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